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Acoustic Emission Based In-process Monitoring in Robot Assisted Polishing

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The applicability of acoustic emission (AE) measurements for in-process monitoring in the Robot Assisted Polishing (RAP) process was investigated. Surface roughness measurements require interruption of the process, proper surface cleaning and measurements that sometimes necessitate removal of the part from the machine tool. In this study, development of surface roughness during polishing rotational symmetric surfaces by the RAP process was inferred from AE measurements. An AE sensor was placed on a polishing tool, and a cylindrical rod of Vanadis 4E steel having an initial turned surface roughness Ra = 3.1 µm was polished using a silicon carbide stone of grit size 600 in 40 polishing passes down to Ra = 0.07 µm. The polishing task was performed in five steps and after 4, 8, 20, 30, and 40 passes the resulting surface roughness was measured. The results show that with proper AE signal processing, the development of surface roughness in the RAP process can be monitored by AE measurement. The AE based monitoring allows in-process determination of the right moment for changing a polishing tool when applying a given set of parameters is no longer effective to create smoother surface, thus improving the efficiency of the process. It also allows for intelligent process control and generally enhances the robustness and reliability of the automated RAP system in industrial applications.

NOMENCLATURE

AE = Acoustic Emission
RAP = Robot Assisted Polishing
CMP = Chemical Mechanical Polishing
FFT = Fast Fourier Transform
STFT = Short Time Fourier Transform

1. Introduction

The importance of the polishing process is well recognized in the industry providing tooling for processes such as forging, die casting, sheet metal forming, injection molding, etc. Since polishing represents the very last step of a long mold making process chain with high quality requirements, any non-conformity resulting in the rejection of a part represents high financial losses because of the cost of the manufacturing operations prior to polishing. Advances in process planning and manufacturing led to the introduction of technologies such as CAD/CAM, High Speed Machining (HSM), Multi-axis CNC machining (Computer Numerically Controlled), Electro Discharge Machining (EDM), etc. These technologies reduced lead time and the need for auxiliary finishing operations, nevertheless, improvement of the surface finish of dies and molds using mechanical, electrical or electro-chemical methods will continue to be a major concern in die manufacturing. It is estimated that from 35% to 50% of all overall die and mold manufacturing time is devoted to surface finishing and polishing [1]. It was reported that around 70% of machine shops in the U.S. and Japan perform polishing by hand while in Germany 66% of the companies have automated polishing equipment [2]. The large share of labor intensive and time consuming hand polishing is due to the fact that the overall mechanism of polishing is still not well understood and our understanding of this technology has remained essentially at an empirical level [3].

The die manufacturing industry would benefit greatly from automated polishing processes that had a high degree of reliability. Unattended machining, which is becoming more and more necessary for cost control, requires very robust processes [4]. Automated polishing experiments have been carried out using CNC machine tools [5-8], robots [9] or specific purpose machines [10]. However, these mechanical systems are limited to specific polishing jobs, and all have the major disadvantage of not being able to control the polishing progress as adequately as experienced polishers can. Lack of process control and of any means of adjusting the polishing conditions in-process reduces the reliability of these systems and delays their acceptance for many industrial applications.

Sensor-based monitoring can serve the dual purpose of process control and quality monitoring, making it possible to improve the robustness and reliability of the process, and will ultimately be part of any fully automated manufacturing environment [11]. Very small uncut chip thickness and material removal at the sub-micron level are characteristic of the polishing process, so that the signal describing the process will always be contaminated by noise from disturbance sources, making robust monitoring very difficult to achieve. Acoustic emission (AE) sensors have shown the greatest sensitivity under the most critical process conditions in precision machining, and the lowest noise level [12]. This is due to the propagation of AE well above the frequencies that are characteristic of machining, e.g. spindle rotational speed or natural resonance frequencies, resulting in a higher signal to noise ratio and increased sensitivity [13]. Successful application in grinding [12, 14], chemical mechanical polishing (CMP) [11, 12, 14] and mechanical polishing [7, 8] has been reported. Ahn [7, 8] reported that die surface roughness during the mechanical polishing process can be indirectly estimated from AE measurements, when an AE sensor is placed on the surface being polished and close to the signal source.

The purpose of this work is to verify the applicability of AE sensing solution for monitoring of surface roughness development in Robot Assisted Polishing (RAP). The focus is on the application of AE based monitoring of polishing rotational symmetric work pieces such as punches, dies, and molds using the RAP process, where the placement of wired AE sensors directly on a rotating work piece is not feasible.

2. Robot Assisted Polishing

The basic idea behind the development of a polishing machine based on STRECON's RAP technology was to develop a machine system that builds on the skills of the craftsmen. Skilled polishers work with a series of steps combining different polishing media and carriers for these media. They are able to bring a surface that is machined by turning, grinding, milling, or EDM from a roughness level of Ra 0.2 — 3.0 μm, down to a mirror or mirror-like surface with a roughness level in the range of Ra 0.01 – 0.03 μm. The working procedure of the skilled hand-polisher ensures that the initial roughness and defects from the preceding manufacturing processes (such as white-layer from EDM) are fully removed before the final polishing steps, thereby securing an optimal function of the surface in the subsequent application. The RAP machine systems must be able to utilize these procedures if they are to take over most of the repetitive work, hence the term: Robot Assisted Polishing. The goal is to develop an industrial RAP machine tool technology that can ensure and maintain the polishing of functional surfaces of the work piece as required by the tool or product design engineer and as specified by the operator. This framework for the design and development process has led to the RAP 225 polishing machine by STRECON shown in Fig. 1.

The machine is built up on a machine housing that contains a main spindle driven by a direct-drive servomotor. A standard industrial robot that generates the main movements is placed in the working cabin holding a key part of the RAP technology: the polishing module (shown on the right side in Fig. 1) that combines a force-loading sub-module with either a pulse based or rotational based polishing sub-module. The force sub-module is able to apply a force orthogonal to the surface in the range of 1 to 30N to the polishing tool, and for the pulsation and rotating driven tools module the controlling parameters such as pulse-frequency or rotational speed can be controlled by the RAP-polishing program. The polishing modules are able to work with all the standard polishing media ranging from coarse to fine stones over coarse diamond on brass or plastic to fine diamond grit paste on wood or felt. Experience from industrial applications shows that by choosing the right combination of polishing media and polishing sequence for the RAP machine it is possible to generate surface roughness levels close to mirror finish [15, 16, 17].

Fig. 1 STRECON's RAP-225 Robot Assisted Polishing machine tool (left); the polishing module close up (right)

3. Methodology

To assess the possibility of monitoring the surface roughness progression from AE measurements during RAP of rotating work pieces, an AE sensor was placed on a polishing tool, the polishing task was split into five stages of polishing and surface roughness measurements were performed after each stage. With suitable AE signal processing, this makes it possible to evaluate a possible correlation between the acquired AE signal and the measured progression in polished surface roughness for fixed process parameters.

3.1 Experimental setup

Experiments were performed on STRECON's RAP-225 polishing machine using a pulsation module (Fig. 1). Polishing was carried out on a cylindrical test-piece made of Vanadis 4E (230 HB) from Uddeholm that was equally divided into seven separated bands, ensuring a clear separation of different polishing bands. The initial surface of the test-pieces was turned to a roughness of Ra = 3.1 μm. Silicon carbide stone of grit size 600 from the American producer Geisswein was used as the polishing tool. Process movements and an indication of AE sensor placement in the setup are depicted in Fig. 2.

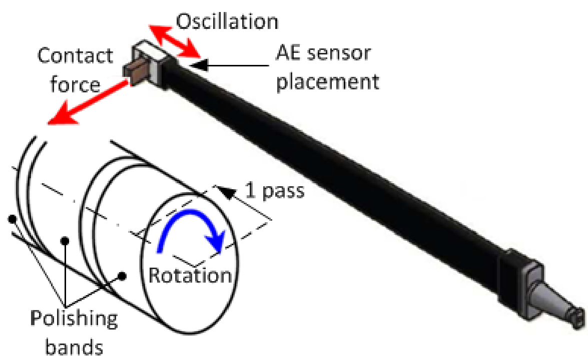

Fig. 2 Indication of the process movements and placement of the AE sensor in the setup, adapted from [18]

Due to the attenuation of AE waves with travelling distance within materials, an AE sensor must be placed as close as possible to the signal source to enhance the signal to noise ratio. The AE sensor was therefore attached by an adhesive tape directly on the polishing arm in direct contact with the polishing tool, using liquid-coupling (silicon grease) between the contact surfaces to obtain the best possible transmission of the AE signal.

The data acquisition system consisted of a piezoelectric AE sensor R15α from the Physical Acoustics Corporation (PAC) connected to an analogue signal pre-amplifier 20/40/60 C (PAC) with built-in band-pass filtering in the range of 20 kHz to 1.2 MHz using 20 dB signal gain. The amplified signal output was directly connected, via coaxial cable, to a multifunction data acquisition board (DAQ) NI USB-6251 with a sampling frequency of 1 MHz and 16-bit resolution. The high sampling frequency of 1 MHz was chosen in order to ensure suppression of signal aliasing and possible loss of signal amplitude due to any high frequencies that were present. A delay of 2 seconds was set during segmentation of the measured data between data acquisition from a buffer and triggering a new measurement. This provided a reduced amount of data while ensuring it sufficient for data post processing.

Surface roughness measurements were conducted by a stylus profilometer MAHR Surftest SJ-210, equipped with a skid pick-up and a 2 μm radius tip, in accordance with ISO 3274:1975 [19].

3.2 Experimental procedure

Polishing was conducted in five steps of 4, 8, 20, 30, and 40 passes on different surfaces (polishing bands) of the test-piece shown in Fig. 2 with the in-process AE measurements. In the present setup, one polishing pass represents 12 mm unidirectional axial travel of a polishing tool along the whole polished surface (one polishing band in Fig. 2). Each of the polishing steps consisted of a number of repeated reversible axial movements of the polishing tool, described by the number of polishing passes (2 passes = 1 reversible movement forth and back). A pulse based polishing module with the process parameters summarized in Table 1 was used.

Surface finish of the produced surfaces was measured and evaluated in terms of arithmetic mean roughness Ra [μm] with 3 measurement repetitions on each resulting surface. An evaluation length ln = 4 mm, low-pass λs = 0 μm and high-pass λc = 0.8 mm profile filtering, according to ISO 3274:1996 [20], were applied.

Table 1 Employed process parameters

Process parameter	Unit	Magnitude
Spindle speed	rpm	300
Robot feed rate	mm/s	1
Pulsation frequency	min^{-1}; [Hz]	3000; [50]
Pulse stroke length	mm	1
Contact force	N	10

4. Results and discussion

4.1 Surface roughness

Measured surface roughness Ra after 4, 8, 20, 30, and 40 passes during the polishing process are shown in Fig. 3. Although measurement was repeated five times, the standard deviations were negligible and so are not shown. The evolution of the surface roughness profile during the polishing process is depicted in Fig. 4. The last profile, resulting from 40 polishing passes, is not shown as it does not indicate any surface improvement from the surface profile resulting from 30 passes. Based on these measurements results, it is obvious that there was no surface improvement after approximately 25 polishing passes.

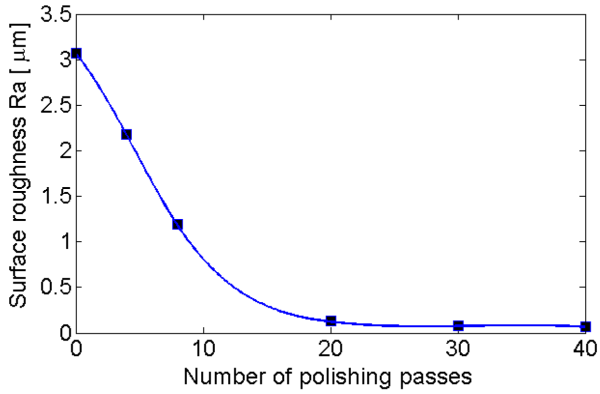

Fig. 3 Surface roughness (Ra) progression during 40 polishing passes

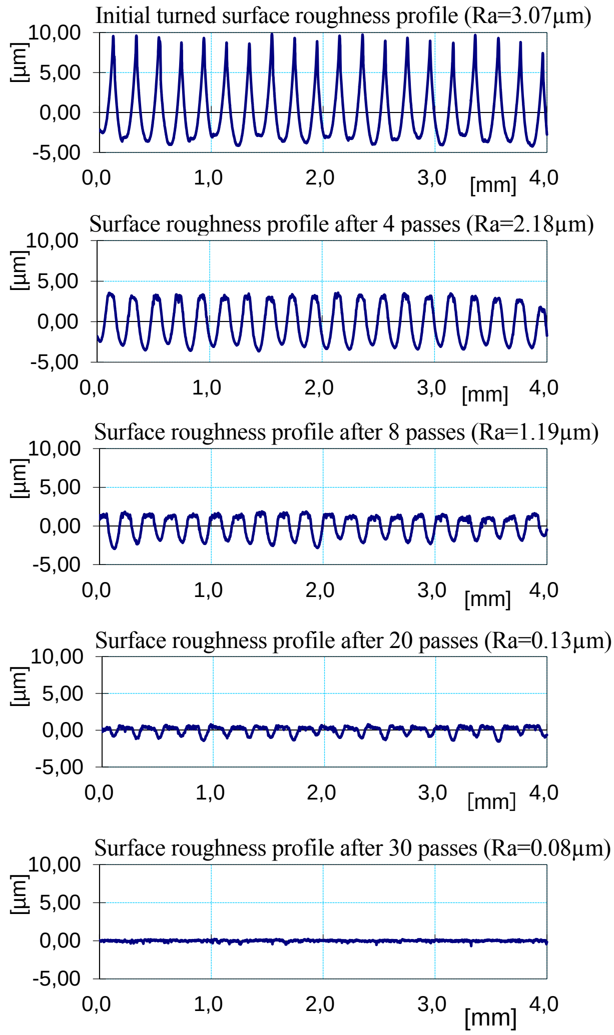

Fig. 4 Evolution of surface roughness profile during polishing

4.2 AE measurements

A representative AE signal acquired during the 40 passes of the polishing process (shown in Fig. 5) contains the sum of the physical phenomena reflecting the polishing process itself, process characteristics, machine tool behavior, tool wear, sensor characteristics, noise, etc.

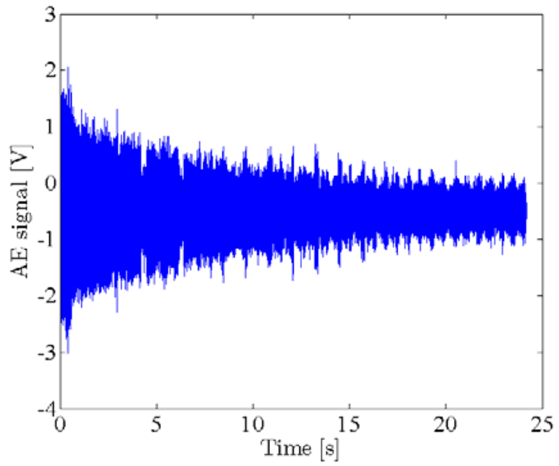

Fig. 5 Concatenated AE signal during 40 polishing passes

In order to provide a robust source for process control by means of AE measurements, the signal must be converted into a meaningful representation reflecting all contributors contained in the signal. Such a representation may reveal sources of signal distortion, which can be suppressed by utilizing additional signal processing tools (e.g. filtering out electrical noise). The AE signal acquired during the polishing process represents a stochastic (non-deterministic) signal, determined both by the predictable actions of the process and by random contributions, having indeterminacy in its future evolution. The signal is of a non-stationary (aperiodic) nature, meaning that parameters such as the mean and variance change over time or position. Spectral (or frequency) analysis by a Fast Fourier Transform (FFT) showing important frequencies contained in the acquired AE signal is depicted in Fig. 6. From the spectral analysis of the signal, three major frequency peaks around 20, 45 and 150 kHz can be distinguished. These three frequency bands were found to be constant signal characteristics of all the five polishing steps with different number of passes.

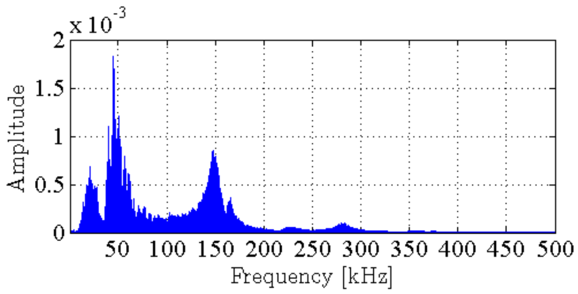

Fig. 6 Concatenated AE signal during 40 polishing passes in frequency domain representation

To gain a better understanding and in order to determine the frequency phase content of these local sections of a signal as it changes over time, a spectrogram using Short Time Fourier Transform (STFT) was applied to the AE data. Calculation of STFT was performed by using the MATLAB function ‘’spectrogram’’. A mathematical description of the function is not discussed here in detail but can be accessed in the literature dealing with digital signal processing, for example in [21]. In Fig. 7, STFT analysis of two different polishing passes, the 1st and 30th respectively, is depicted to show changes in frequency spectrum over polishing time. The Y axis represents the time period of 1 polishing pass. This time period of 0.6 second does not represent the whole polishing pass in correct time duration, but represents concatenated measured data segments of a buffer size of 0.1 s with a trigger delay of 2 seconds between two subsequent data acquisitions. With a robot feed rate of 1 mm/s over the 12 mm long polishing band, this results in acquired 6 data segments of 0.6 s in total, while the remaining 11.8 s were not acquired due to the trigger delay. Therefore such representation completely describes the whole polishing pass while considerably reducing the amount of data acquired and thus also the computationally expensive data processing.

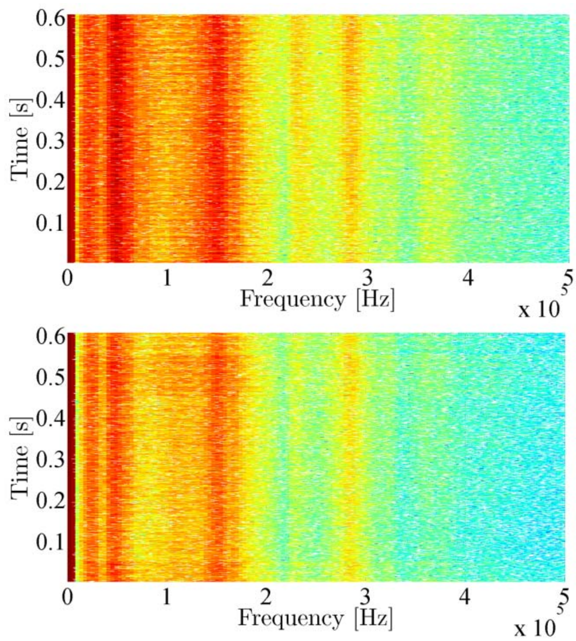

Fig. 7 STFT analysis of the acquired AE signal, window = 256 data points, no overlapping, FFT size = 256 data points; 1st polishing pass (top), 30th polishing pass (below)

Spectrogram in Fig. 7 reveals a time dependency of all the three main frequency ranges representing the process. Since all process movements and parameters were kept constant, a constant frequency phase in the AE signal would represent the intrusive signature of machine tool behavior. The decreasing amplitude of the acquired AE signal and its frequency content is thus deemed to be directly correlated with the progressive improvement of the surface finish with processing time. This provides a baseline for better understanding of the physics of the process, although higher frequencies may not be captured due to the insufficient sensitivity of the sensor for capturing events of higher frequencies. There is no obvious signal distortion or presence of abrupt events, a clearly decreasing signal trend and a time-dependent frequency content of the acquired signal, so it was considered that the band pass filtering built into the signal pre-amplifier was sufficient and that there was no need for additional signal filtering.

Since the signal as a function of time x(t) is of finite energy with Fourier Transform X(t), its energy can be expressed by the following relationship:

$$E_x = \int_{-\infty}^{\infty} |x(t)|^2 dt = \int_{-\infty}^{\infty} |X(F)|^2 dF \quad (1)$$

In order to show how the AE signal energy is distributed over the polishing time, the signal's power characteristic given by $|x(t)|^2$ is plotted in Fig. 8.

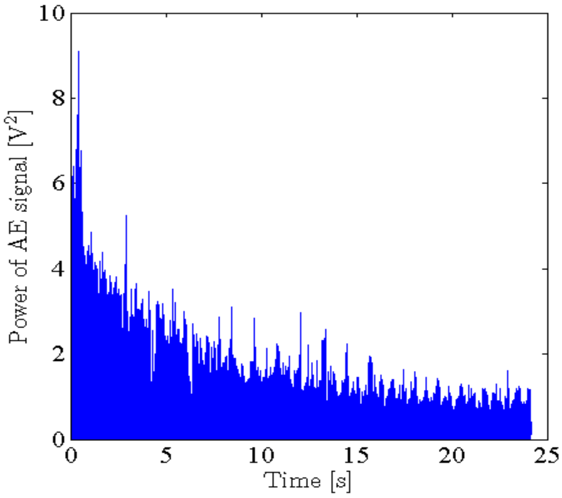

Fig. 8 Concatenated AE signal power during 40 polishing passes

Fig. 8 shows a clear decreasing trend in the AE signal power as a function of the polishing time. At this stage, it is difficult to formulate a robust definition of the end of the polishing process due to the redundant information contained in the signal. One of the most commonly used algorithms for capturing an important trend in a data set while leaving out noise or other fine-scale structures/rapid phenomena is the "moving average", replacing each point in the signal with the average of "M" adjacent points. Data smoothing by means of a moving average system with window size of 1000 data samples was applied to the calculated AE signal power (Fig. 8), resulting in the signal envelope shown in Fig. 9.

4.3 Correlation between surface roughness and AE measurements

The application of a moving average system provides a smooth approximation of the process trend reflected in the AE data which can be directly correlated with the surface roughness progression by means of 6 roughness measurements made after a predetermined number of polishing passes (section 4.1). A trend reflecting the surface progression in the polishing process is highlighted by spline fitting of the measured arithmetic mean roughness Ra for direct evaluation of a relative correlation with the trend in AE data in Fig. 9. From the figure, a clear correlation between decreasing average power of AE signal and measured surface roughness Ra can be seen. Such behavior was found to be repeatable in all the five polishing steps with different number of polishing passes.

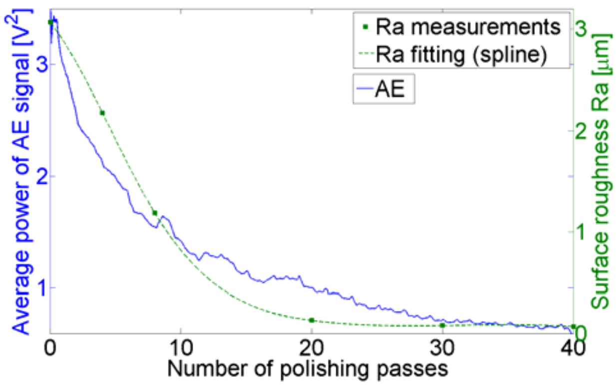

Fig. 9 Correlation of the average power of AE signal and surface roughness Ra during 40 polishing passes

CONCLUSION AND OUTLOOK

An investigation on the applicability of acoustic emission measurement for monitoring Robot Assisted Polishing was carried out. Based on the results, the following conclusions were drawn:

- Development of surface roughness in the polishing process can be monitored by AE measurement. A clear correlation between decreasing AE amplitude and surface roughness Ra was found;
- Placement of an AE sensor in direct contact with a polishing tool makes it possible to monitor the polishing process of rotating work-pieces, where placement of a wired AE sensor on the work-piece being polished is not feasible;
- The proposed method makes it possible to determine the right moment for changing a polishing tool when applying a given set of parameters is no longer effective to create smoother surface, thus improving the efficiency of the process;
- The proposed AE based approach is suitable for continuous in-situ monitoring of the RAP process and thus enables intelligent process control. This enhances the robustness and reliability of the automated polishing system.

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